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Short communication

Barefoot vs shod walking and jogging on the electromyographic activity of the medial and lateral gastrocnemius

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ABSTRACT

Gastrocnemius weakness is associated with Achilles tendinopathies and muscle strains, with the medial gastrocnemius (MG) more commonly injured than the lateral gastrocnemius (LG). Walking and jogging are common in daily activities and sports, and biomechanical differences between shod and barefoot exercise may influence MG and LG activation. Understanding these activation patterns could help optimize training programs for injury prevention and/or rehabilitation. The aim was to compare MG and LG electromyographic activity during walking and jogging, both shod and barefoot. Twenty-nine participants (25.28 ± 4.53 years, 171.31 ± 0.76 cm, 72.68 ± 6.36 kg) completed a warm-up followed by 1 min of walking (80–99 steps/min) and jogging (130–150 steps/min) in both conditions (barefoot and shod, random order). Electromyographic signals were recorded using wearable devices (mDurance Solutions S.L., Granada, Spain; 1024 Hz sampling rate). We measured the root-mean-square (RMS) amplitudes for an entire stride cycle and digitally filtered the signals. For analysis, we normalized electromyographic values to the average peak values obtained during two sprints. We analyzed differences with a repeated-measures analysis of variance. Significant effects of condition (barefoot-shod) and gastrocnemius (MG-LG) were observed (all $p \leq 0.023$, $\eta p^2 = 0.17$–0.39), with higher MG activation compared to LG in the barefoot conditions ($p = 0.004$–0.027, $d = 0.72$–0.83), and nonsignificant differences between muscles in the shod conditions ($p > 0.05$). Shod exercise compared to barefoot resulted in lower MG activation ($p = 0.001$–0.003, $d = 0.62$–0.63) and non-significant differences in LG activation. These results indicate that barefoot walking and jogging increase MG activation compared to shod conditions, with no differences in LG activation. Additionally, footwear reduces differences between MG and LG.

1. Introduction

The gastrocnemius muscle has two heads, the medial (MG) and lateral gastrocnemius (LG) (Bordoni and Varacallo, 2022). These muscles facilitate ankle plantarflexion, knee flexion, absorb kinetic energy, and stabilize the tibia and foot during gait and jogging (Honeine et al., 2013; Ugbolue et al., 2021). The MG and LG originate from the femur's medial and lateral epicondyles, respectively, and form the Achilles tendon with the soleus (Dalmau-Pastor et al., 2014).

The MG and LG exhibit functional differences. For instance, a toes-out foot position during heel raises activates more the MG (Cibulka et al., 2017). Oppositely, a toes-in foot position can increase the LG activation (Cibulka et al., 2017; Riemann et al., 2011). Biomechanical differences between shod and barefoot exercise may also affect MG and LG activation. For instance, running barefoot increases plantar flexion angle and moment and posterior chain muscle preactivation, and modifies foot-strike patterns (Franklin et al., 2015).

Understanding gastrocnemius activation is relevant for several

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reasons. First, the literature is unclear on optimizing hypertrophy for specific muscles (Alix-Fages et al., 2022). Obtaining information on gastrocnemii activation during specific tasks can help in this regard. Gastrocnemius weakness is linked to Achilles tendinopathies and muscle strains (Cibulka et al., 2017), with the MG being more commonly injured than the LG (Hsu and Chang, 2022). Walking and jogging are common in daily activities and sports. Being aware of the activation of the MG and LG during walking or jogging, shod or barefoot, can help optimize training programs for injury prevention and/or rehabilitation. To date, no study has analyzed electromyographic differences between MG and LG in shod vs barefoot walking and jogging.

This study aimed to compare the MG and LG neuromuscular activity during barefoot/shod walking and jogging. Additionally, considering that gastrocnemius weakness is associated with triceps surae injuries, we sought to identify which, barefoot or shod, results in the greatest activation of both gastrocnemius heads. We hypothesized that (i) shod walking/jogging would reduce neuromuscular differences between the LG and MG, and (ii) barefoot walking/jogging would increase the muscle activation of both heads.

2. Materials and methods

2.1. Experimental design

The protocols followed the Declaration of Helsinki and were approved by the Ethics Committee of the University of Valencia (approval: 1973315). Participants provided written informed consent.

2.2. Participants

We included healthy, physically active participants (nonprofessional athletes), aged 18–40, engaging in at least 30 min/day of moderate-to-high intensity activities involving jogging (e.g., soccer, running) at least three days/week, with no injuries in the past six months. Exclusion criteria were body mass index ≥30 kg/m^2, history of lower limb surgery, neurological or autoimmune conditions, or any exercise contraindication.

A power analysis indicated that 28 participants were sufficient for a power of 0.80, $\alpha = 0.05$, and a moderate-large effect size (f) of 0.40. Finally, 29 volunteers (24.1 % females; see Table 1 for characteristics), from recreational sports clubs in Valencia (Spain) participated.

2.3. Procedures

This study employed a single session. Participants received a visual-verbal explanation, and descriptive variables (age, sex, health, anthropometry) were collected. At this point, participants were familiarized with the standardized walking and jogging pace/cadence, aided by a metronome and verbal feedback. The walking cadence was set at 80–99 beats (steps) per minute (medium walking pattern) (Tudor-Locke et al., 2011); the jogging cadence at 130–150 beats (steps) per minute (slow jogging, < 7 km/h) (Harrington et al., 2011).

After familiarization, sensors were allocated by an EMG-experienced researcher (see EMG Measurements Section). A standardized warm-up followed: 5 min jogging at the predetermined pace, dynamic stretching (6 reps for major muscles), and 2 × 40m submaximal runs at 80 % of perceived maximum speed.

The experimental procedures involved four randomly ordered conditions (https://www.random.org). Participants walked or jogged uninterruptedly along an 8-meter walkway for 1 min, with a 2-minute rest between tries. A researcher ensured accurate cadence. EMG in the lower limb is stable after about 3–50 strides (Arsenault et al., 1986). Therefore, to avoid interindividual variability, we only considered the root-mean-square (RMS) amplitudes (expressed in μV) from six strides (three each leg) of the central part of the last four 8-m distances, totaling 96 strides per subject and condition. The investigator in charge manually marked the start and end of the last four 8-meter distances to be measured for each condition. Then, we identified each stride by examining the EMG curve, with minimum EMG amplitude registered between contractions being used to identify strides. A graphical example of three strides registered during one of the 8-meter distances is presented in Supplementary Material 1.

Finally, participants performed two 40-meter sprints to obtain activation peaks (Chuang and Acker, 2019), with a 5-minute rest between sprints. We used the average of the two peak values for normalization. All EMG data are presented as a percentage (%) of the maximum activation during the sprint.

Table 1
Characteristics of the participants (n = 29).

Variable	Mean	Standard deviation
Age (years)	24.83	4.32
Height (cm)	174.49	8.07
Body weight (kg)	69.20	11.17

2.4. EMG measurements

Initially, EMG was recorded from both legs, but only right leg data were analyzed, as no significant differences were found between legs ($p = 0.619$, $\eta p^2 = 0.01$).

Before electrode placement, the skin was shaved and cleaned. Surface electrodes were placed on the MG and LG bellies according to SENIAM criteria (Hermens et al., 2000). Chlorinated silver pre-gelled bipolar surface electrodes (Kendall™ Medi-Trace, Covidien, Barcelona, Spain) were used with a 10mm interelectrode distance. The reference electrode was placed on the fibular lateral malleolus. Two synchronized two-channel wearable devices coupled to a Shimmer branch inertial sensor (Realtime Technologies Ltd, Dublin, Ireland) with 16-bit analog-to-digital (A/D) conversion were employed, with a sampling rate of 1024 Hz. The wearable sensors were located at the mid-internal side of the tibia at electrode level. Electrodes, connectors, cabling, and pre-amplifiers were secured with cohesive bandages to prevent movement artifacts (Akuzawa et al., 2023; Kelly et al., 2015).

The EMG signal was monitored using validated mDurance software (mDurance Solutions S.L., Granada, Spain). Raw EMG signals were stored for subsequent evaluation and digitally filtered using a fourth-order "Butterworth" bandpass filter between 20 and 450 Hz. A high-pass cutoff frequency of 20 Hz reduced movement artifacts (Ferri-Caruana et al., 2022). An algorithm flagged signals of less than 0.05 V (indicative of signal drop) or greater than 2 V (typically a signal spike or signal depolarization) to avoid spikes. After normalization, signals of less than 5 % (minimum limit of accurate EMG measurement) or greater than 100 % were flagged (Chuang and Acker, 2019). All marked signals were visually inspected and accepted if they showed no signs of artifact.

2.5. Statistical analysis

Statistical analyses were performed using SPSS 28.0 (IBM Corp, Armonk, NY, USA) and G*Power 3.1.9.6 (Faul et al., 2007). Results are presented as mean ± standard deviation, 95 % confidence interval (95 %CI), and mean difference (m.d.). Significance was set at $p < 0.05$.

The Shapiro-Wilk test assessed normality. Most variables showed a normal distribution ($p > 0.05$). Only the LG EMG during barefoot and shod walking, and MG during shod jogging were non-normal. Parametric tests were used as they are robust to violations of normality (Blanca et al., 2017).

We conducted a two-way analysis of variance (ANOVA) with condition (barefoot, shod) and gastrocnemius (lateral, medial) as within-subject factors. The effect size was evaluated with eta partial squared (ηp2) ($0.01 < \eta p2 < 0.06$ small effect, $0.06 \leq \eta p2 \leq 0.14$ medium, and $\eta p2 > 0.14$ large). Four pairwise post-hoc comparisons were evaluated using the Bonferroni correction. Post-hoc comparisons effect size was calculated as Cohen's d with Hedges' corrections (Lakens, 2013), reported as unbiased Cohen's d (dunb) (Cumming, 2014), with dunb < 0.50 being a small effect, 0.50 ≤ dunb ≤ 0.79 moderate, and dunb ≥ 0.80 large (Cohen, 1988).

3. Results

3.1. Main effects and Interactions

3.1.1. Walking

Significant effects were found for the condition (barefoot, shod; $F[1,28] = 11.11$, $p = 0.002$, $\eta p^2 = 0.28$), gastrocnemius (lateral, medial; $F[1,28] = 5.80$, $p = 0.023$, $\eta p^2 = 0.17$), and interaction condition*gastrocnemius ($F[1,28] = 17.65$, $p < 0.001$, $\eta p^2 = 0.39$) (Fig. 1).

3.1.2. Jogging

Significant effects were observed for the condition ($F[1,28] = 10.33$, $p = 0.003$, $\eta p^2 = 0.27$), gastrocnemius ($F[1,28] = 11.65$, $p = 0.002$, $\eta p^2 = 0.29$), and condition*gastrocnemius ($F[1,28] = 12.83$, $p = 0.001$, $\eta p^2 = 0.31$) (Fig. 2).

3.2. Medial vs lateral gastrocnemius

The MG showed significantly more activation than the LG during barefoot walking (m.d. 2.60 %, 95 %CI[0.88–4.33], $p = 0.027$, dunb = 0.72) and jogging (m.d. 3.89 %, 95 %CI[1.79–5.99], $p = 0.004$, dunb = 0.83), but not during shod walking ($p > 0.999$, dunb = 0.21) or jogging ($p = 0.133$, dunb = 0.43). The effect sizes in the shod conditions were small (dunb = 0.21–0.43) and moderate-large in barefoot (dunb = 0.72–0.83) (Table 2).

3.3. Barefoot vs shod

Wearing shoes significantly reduced MG activation compared to barefoot walking (m.d. 2.27 %, 95 %CI[1.19–3.34], $p = 0.001$, dunb = 0.63) and jogging (m.d. 3.00 %, 95 %CI[1.44–4.56], $p = 0.003$, dunb = 0.62). There were no significant differences in LG activation between shod and barefoot walking ($p > 0.999$, dunb = 0.07) or jogging ($p > 0.999$, dunb = 0.20) (Table 2).

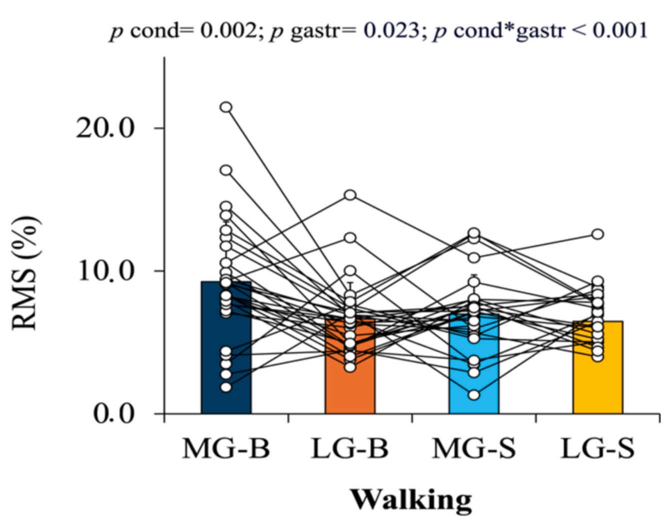

Fig. 1. Medial (MG) and lateral (LG) gastrocnemius activation (root mean square, RMS) during barefoot (B) and shod (S) walking. The bars present the mean for each condition and the dots and lines represent the individual values and variation of each participant.

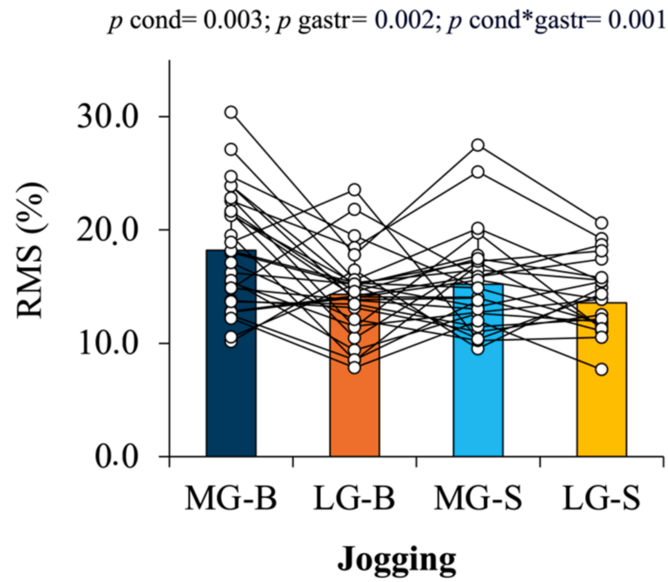

Fig. 2. Medial (MG) and lateral (LG) gastrocnemius activation (root mean square, RMS) during barefoot (B) and shod (S) jogging. The bars present the mean for each condition and the dots and lines represent the individual values and variation of each participant.

4. Discussion

This is the first study comparing MG and LG activation during barefoot and shod walking and jogging. The main finding is that the MG showed significantly more activation than the LG during barefoot walking and jogging, while nonsignificant differences existed in the shod conditions.

Consistent with our first hypothesis, using shoes reduced the differences between the MG and LG. Although we did not measure muscle forces or joint moments, this aligns with research showing increased MG muscle force during barefoot running, but no difference in the LG (Sinclair et al., 2015). We can, therefore, speculate that the increased force in the MG entails greater EMG activation (Kaminski and Royer, 2005). Another potential reason derives from differences in the foot strike and/or increases in the Achilles tendon elastic strain energy during barefoot running (Bonacci et al., 2022). The increased tendon compliance may result in the MG muscle fibers remaining shorter and operating far from their optimal lengths (Uchida et al., 2016). As a result, we can hypothesize that greater activation is required to produce the necessary plantarflexion moment (Bonacci et al., 2022).

Footwear can store and reutilize elastic energy (Willwacher et al., 2013), requiring less muscle–tendon work than barefoot (Bonacci et al., 2022). Our results show MG activity increases, while the LG remains unaffected, partially confirming our second hypothesis. This could potentially be due to greater plantar flexion moments and angles in barefoot running (Bonacci et al., 2022; Franklin et al., 2015; Fredericks et al., 2015; Murphy et al., 2013). Since the MG is the main plantar flexor in running (Tsuji et al., 2015), differences in footwear may affect this muscle more. This is consistent with studies showing greater MG activity during barefoot running compared to shod (Lucas-Cuevas et al., 2016) and nonsignificant differences in the LG (Beierle et al., 2019).

Although walking and jogging are not targeted exercises for gastrocnemii training, they are common in daily activities and sports. Higher muscle activation reflects greater limb loading (Beierle et al., 2019), and gastrocnemius weakness is linked to injuries (Cibulka et al., 2017). These findings can guide training and rehabilitation, with barefoot training potentially increasing MG workload, while shoes may reduce stress in rehabilitation contexts (e.g., after a muscle strain or Achilles tendinopathy rehabilitation). It should be borne in mind that the safety

Table 2
Descriptive results of each condition of study.

Exercise	Cond.	Gastr.	Mean (%)	Std. Dev.	95 % CI		Sig.	Cohen's dunb
					Lower	Upper		
Walking	Barefoot	Lateral	6.65$^{(>0.999)}$	2.79	5.72	7.08	**0.027**	0.72
		Medial	9.25$^{\#(0.001)}$	4.14	8.38	10.88		
	Shod	Lateral	6.47	1.99	5.60	6.82	>0.999	0.21
		Medial	6.99	2.74	6.67	8.80		
Jogging	Barefoot	Lateral	14.32$^{(>0.999)}$	3.86	12.70	15.37	**0.004**	0.83
		Medial	18.21$^{\#(0.003)}$	5.20	16.65	20.23		
	Shod	Lateral	13.57	3.21	12.38	14.39	0.133	0.43
		Medial	15.21	4.19	14.42	17.07		

Significant differences between conditions.
Cond.: condition; Gastr.: gastrocnemius analyzed; Std. Dev.: standard deviation; CI: confidence interval; Sig.: significance (Bonferroni adjusted p-value).

of the initiation in barefoot running is multifactorial (Tam et al., 2016).

5. Limitations and future research

We subjectively supervised participants' technique to ensure "common form," but did not unify participants according to their foot strike pattern. Jogging barefoot promotes a forefoot strike pattern, while shod jogging typically shows rearfoot or variable strike patterns (Murphy et al., 2013). These strike differences between conditions might influence the results. Future studies could perform sub-analyses according to running forefoot or rearfoot technique and foot position, sports discipline, athletic levels, and/or barefoot experience, as activation patterns may change in trained individuals (Fleming et al., 2015).

Second, plantar flexion angle and moment are reduced during shod walking/running compared to barefoot (Bonacci et al., 2022; Franklin et al., 2015; Fredericks et al., 2015; Murphy et al., 2013), but we did not measure plantar flexion. Therefore, our hypothetical explanations regarding the MG and LG differences should be interpreted cautiously.

Lastly, triceps surae activation changes throughout the gait/running stride cycle (e.g., propulsion phase, swing) and we did not differentiate the activation by phases. Future studies should analyze activation patterns across the different stride phases synchronizing the EMG with video or inertial sensors (Akuzawa et al., 2023).

6. Conclusions

The MG showed higher activation levels compared to the LG, particularly in barefoot conditions. Shoes reduce the activation differences between both gastrocnemius heads. Barefoot compared to shod resulted in higher MG activation (no differences in the LG). These findings are useful to individualize training programs and assess the appropriateness of barefoot training.

Data availability statement

Data will be made available upon reasonable request to the corresponding author.

CRediT authorship contribution statement

Ana Ferri-Caruana: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Elena Cardera-Porta:** Resources, Project administration, Methodology, Investigation, Conceptualization. **Javier Gene-Morales:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Angel Saez-Berlanga:** Writing – original draft, Visualization, Methodology. **Pablo Jiménez-Martínez:** Software, Resources, Investigation. **Alvaro Juesas:** Writing – review & editing, Visualization, Supervision, Formal analysis. **Juan C. Colado:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.112371.

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